Analysis of Recorded and Simulated Far-Field Ground Motion From the Source Physics Experiment

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Overview

***Objective**: Improve understanding of the excitation and propagation of seismic waves, especially shear waves, from underground explosions.*

Approach:

- *Simulate near-field ground motion from underground SPE3 explosion using a physics based source model coupled with far-field viscoelastic wave propagation*
- *Compare with observed waveforms from Source Physics Experiment.*
- *Analyze path effects (scattering, topography, and structural variations) at close distances (< 20 km)*

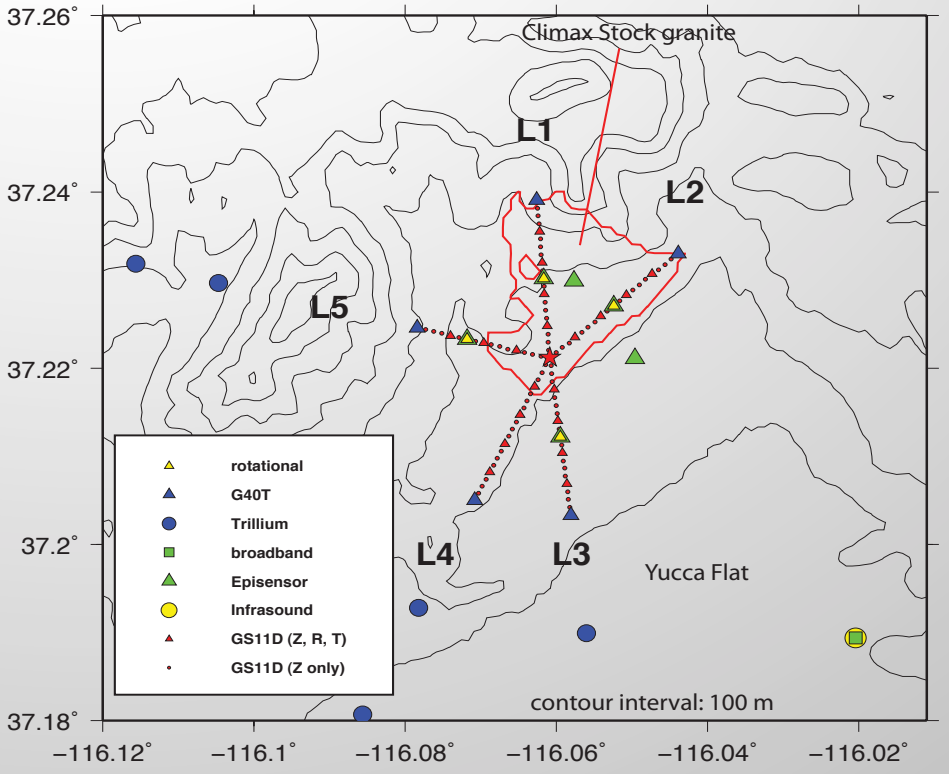
- ***Long-term Goal**: Create a physics-based end-to-end model for monitoring that couples hydrodynamics to elastics and allows for both scenario prediction and detailed analysis of observed signals*

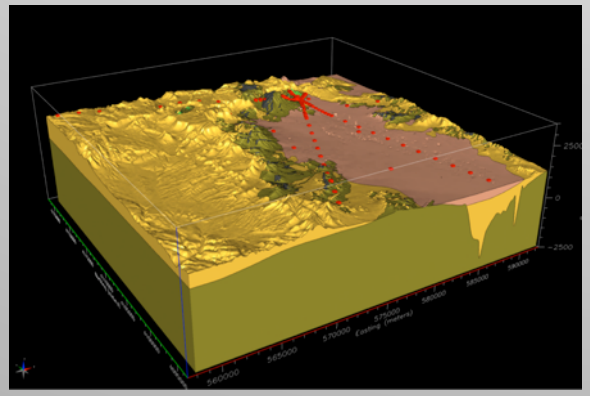
SPE Shots

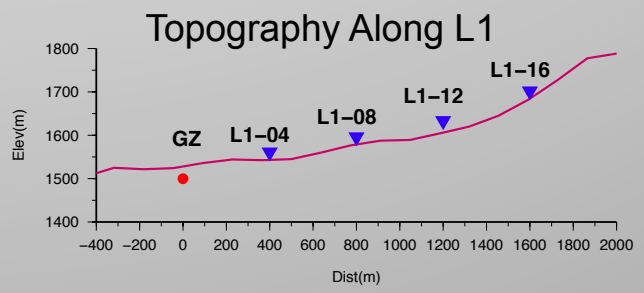
- Emplaced in granite
- SPE1: 100 kg TNT at 55 m
- SPE2: 1000 kg TNT at 45 m
- SPE3: 1000 kg TNT at 45 m

Sensors

- Array of near-field borehole and surface accelerometers
- Instruments deployed along 5 radial lines out to 20 km
- Mix of short-period and broadband
- Infrasound

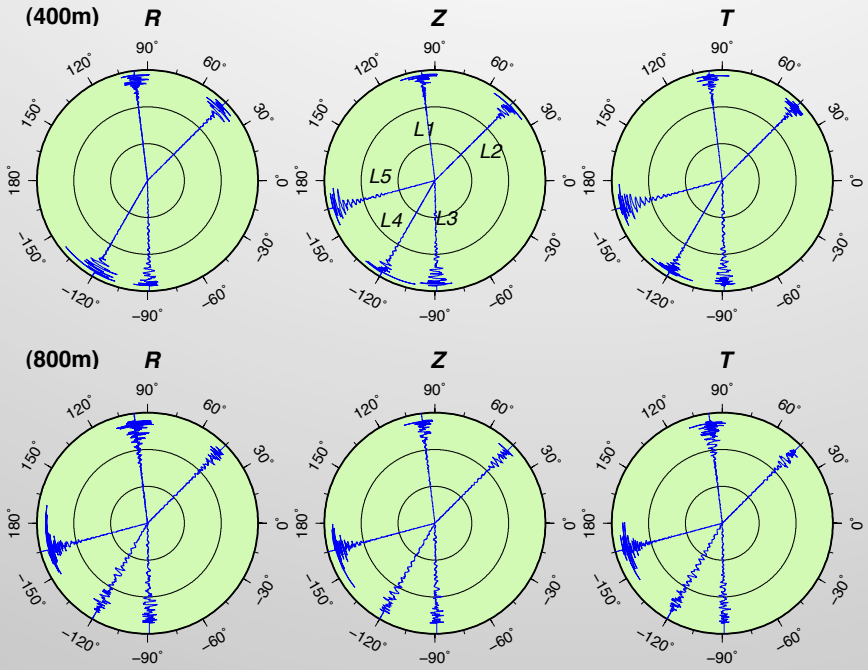






Observed Far-Field Shear Wave Energy

Broad-Band



400m

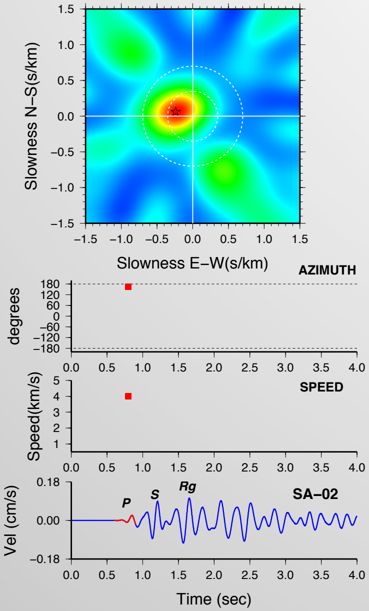
800m

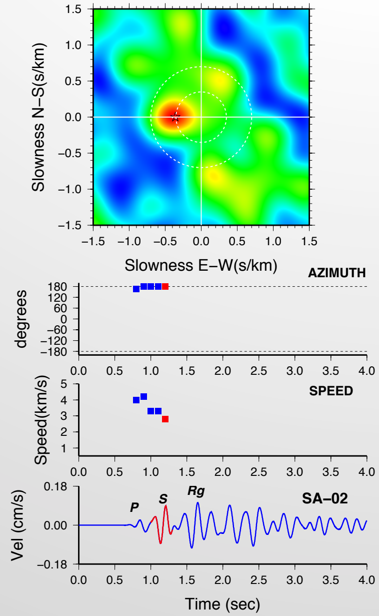
Significant shear wave energy on the tangential component

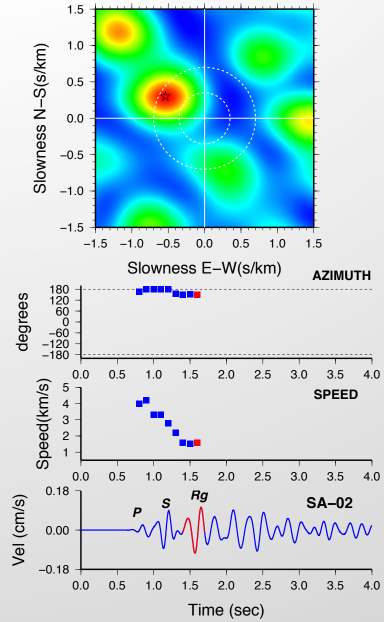
Causes:

- source effects
- wave propagation effects?
  (structural heterogeneity, surface topography)

FK Analysis Using Small Array Data



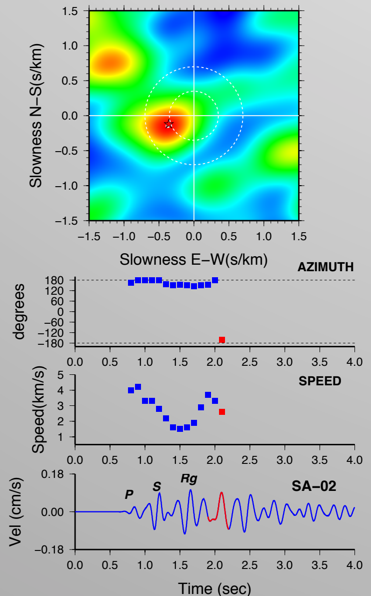


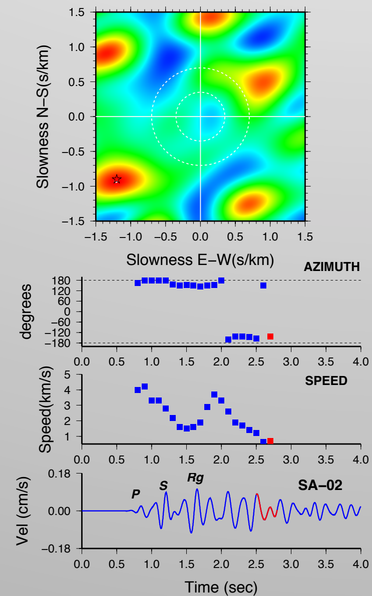


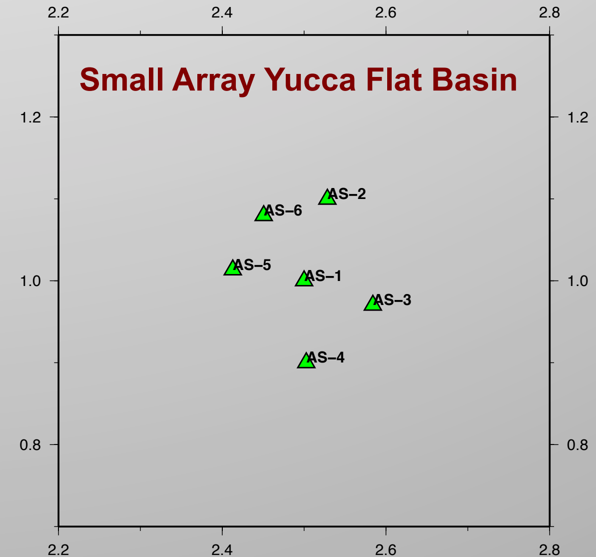
Azimuth

Apparent Velocity

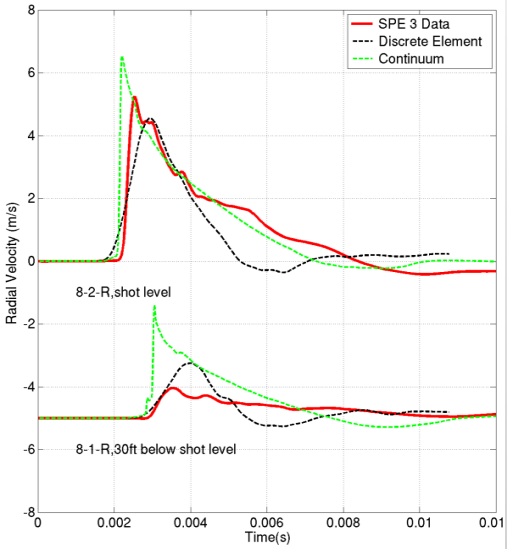
Recorded Motion

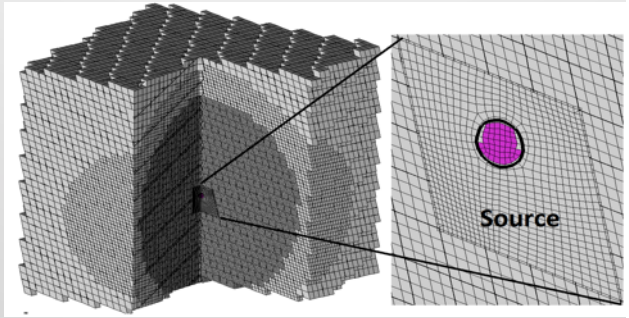


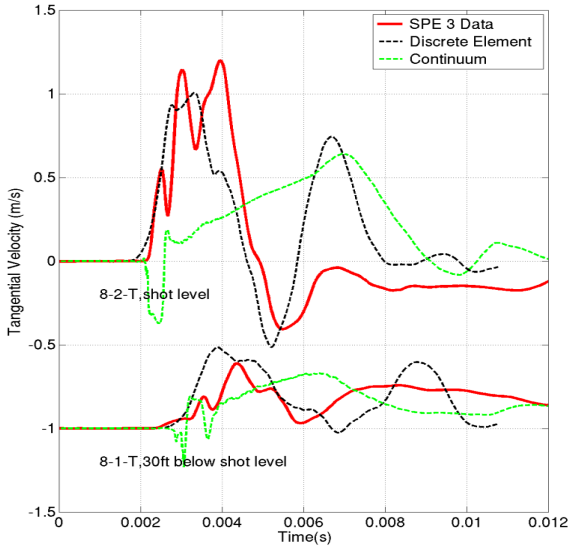




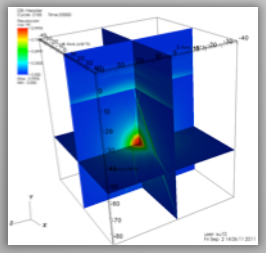
S-waves are produced in the near-field and seem to be consistent with motion on joints



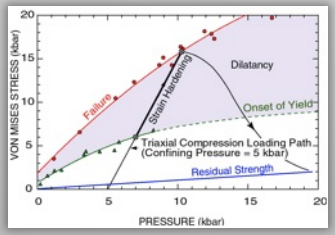




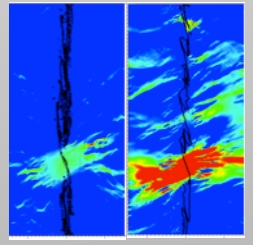
Efforts are underway to improve the quantitative agreement with the near field data and correlate the observed anisotropic behavior to the underlying physical mechanisms



faults & geologic layers

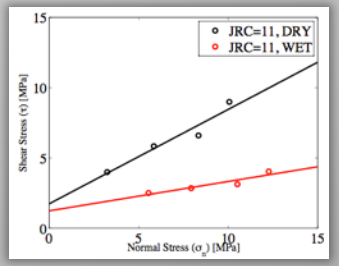


Constitutive behavior of the rock



Joint properties

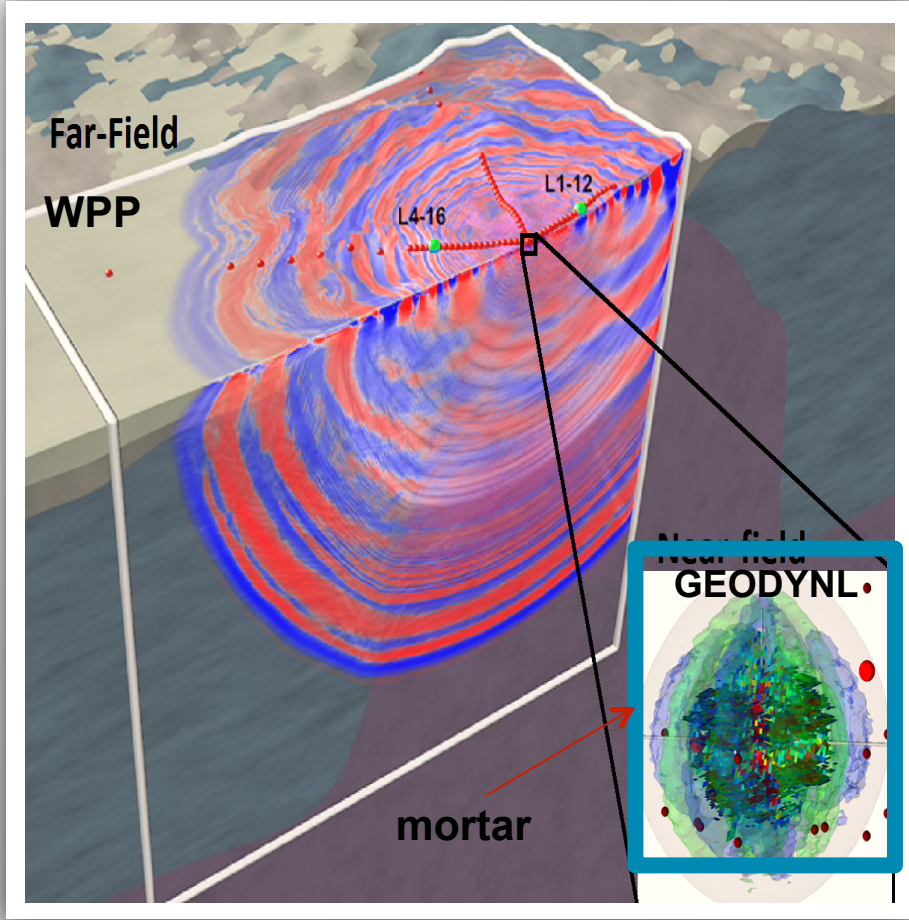
after Vorobiev et al



Effect of saturation

Near-Field and Far-Field Coupling

- **One-way coupling** between nonlinear, inelastic near-field and linear, visco-elastic far-field regions using a padding mortar space in 3D.
- **Near-field:** 3D Lagrangian hydrodynamics code with non-linear material response (GEODYN-L)
  - Explosion loading
  - Compressional and tensile failure, yielding, porosity, cavity formation
  - source mortar embedded within finite difference model
- **Far-field: 3D-FDM (WPP)**
  - Driven by interpolated time series from GEODYN model
  - Signals propagated through complex 3D velocity model of geology to distances of 10's of kms
  - Coupling verified and validated.

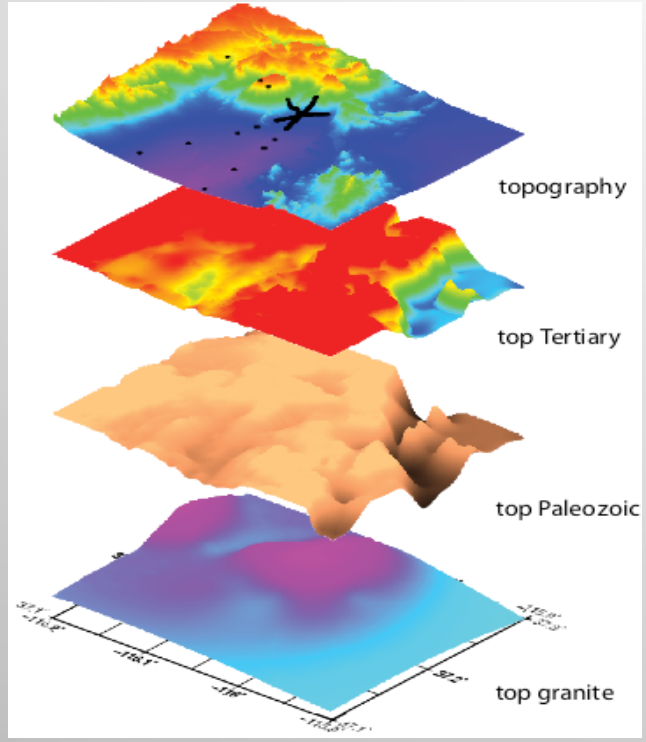


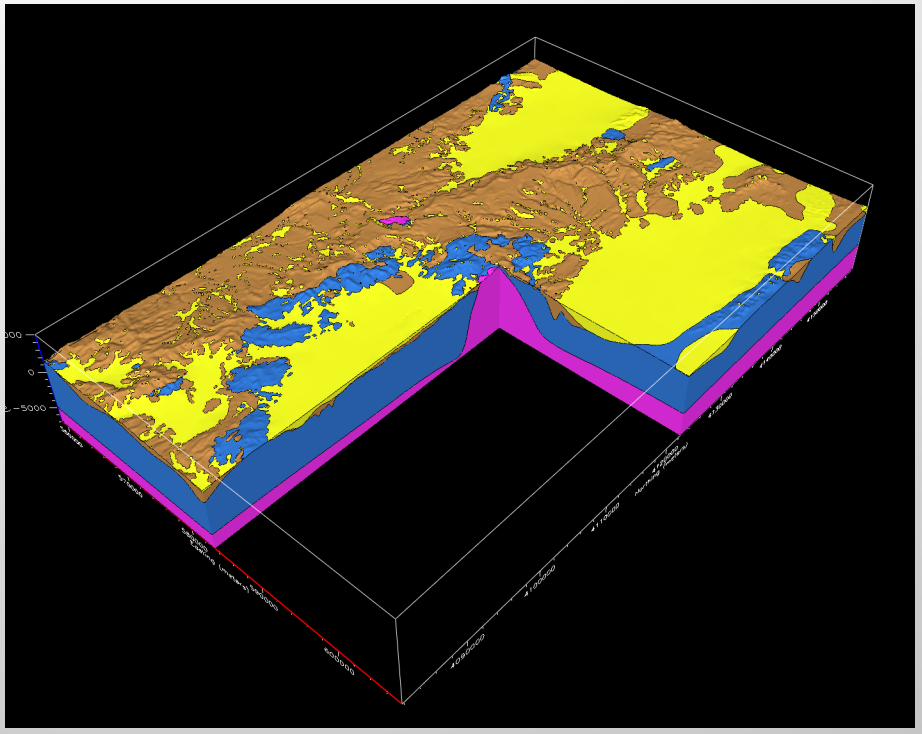
WPP

3D finite-difference code Curvilinear grid for topography, mesh refinement, viscoelastic model .Designed for massively parallel systems

3D Underground Structure

Large Scale Constraints of the 3D Velocity Model





(Wagoner,2012)

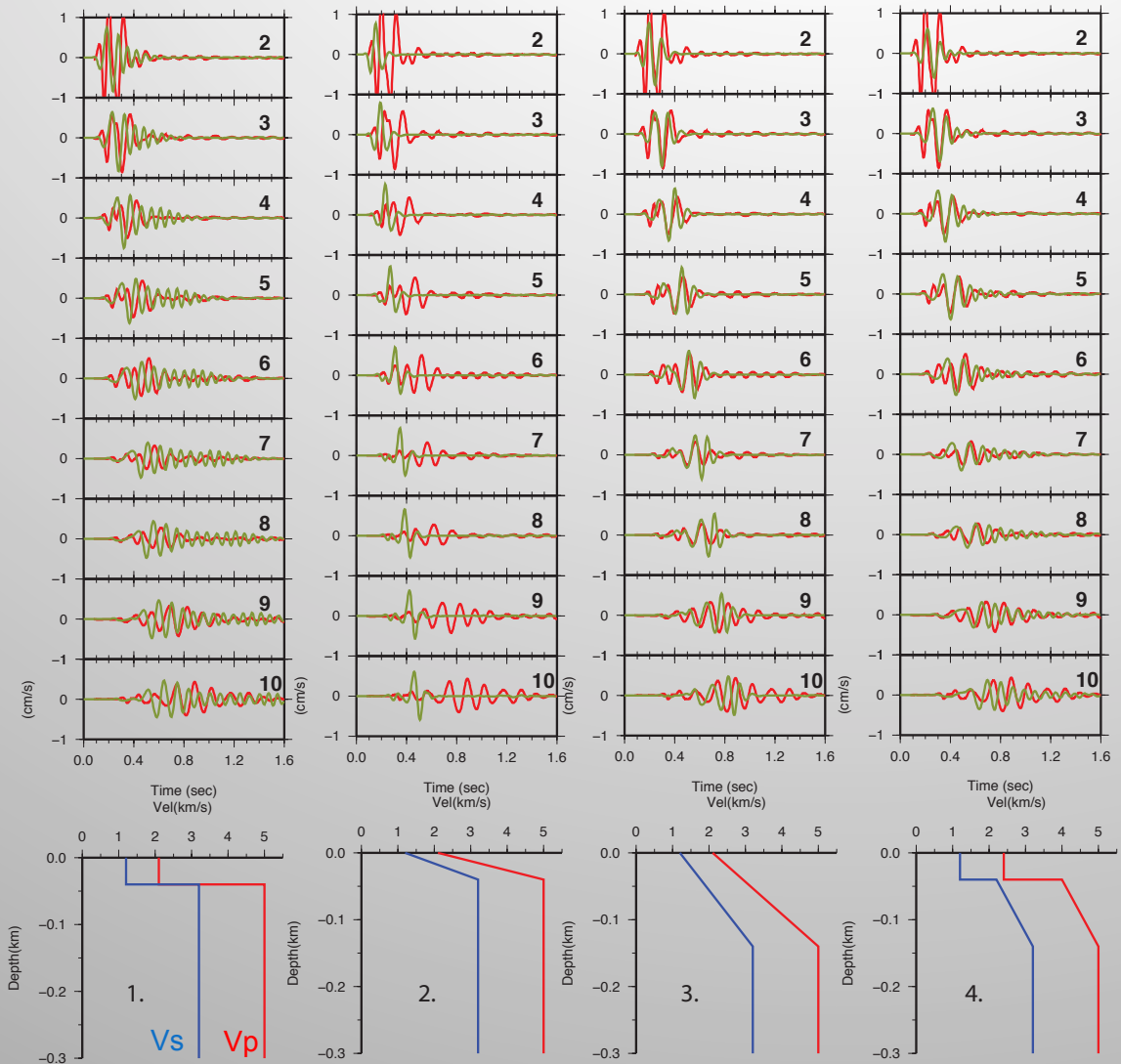
3D Model Based on
- Geology
- Surface mapping
- Boreholes
- Geophysical models

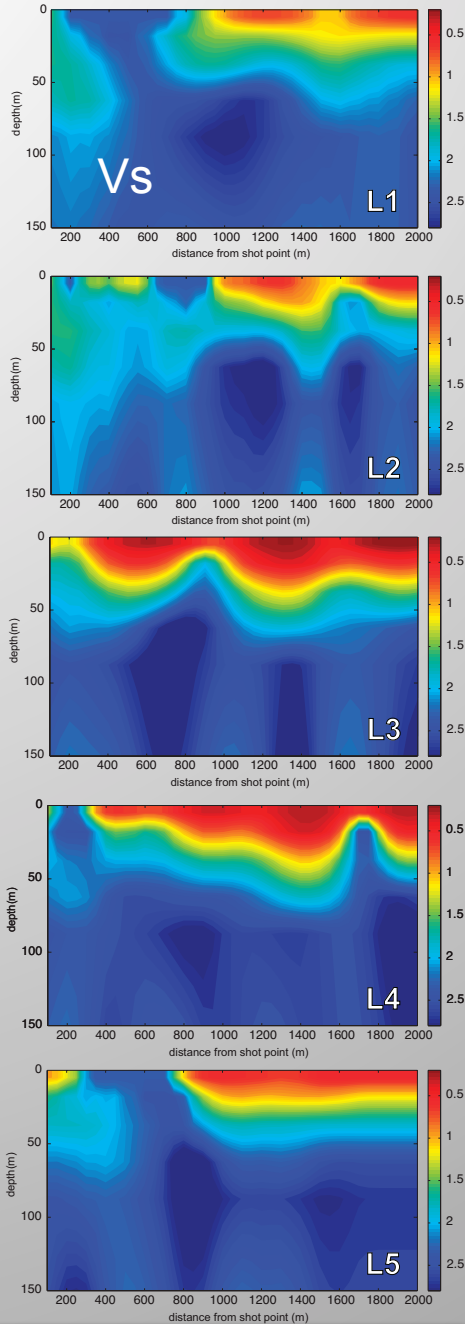
Lithology	Vp(km/s)	Vs(km/s)	
Softer Granite	4.34	2.50	H=60m
Granite:	6.20	3.58	no gradient
Paleozoic:	5.60	3.24	small gradient
Tertiary:	4.20	2.42	small gradient
Quaternary:	3.00	1.50	no gradient
Top Quaternary	2.00	0.90	H=80m

Stochastic Small Scale Heterogeneity (l=1km,up 15%)

2.5D Modeling of Shallow Structure in Granite

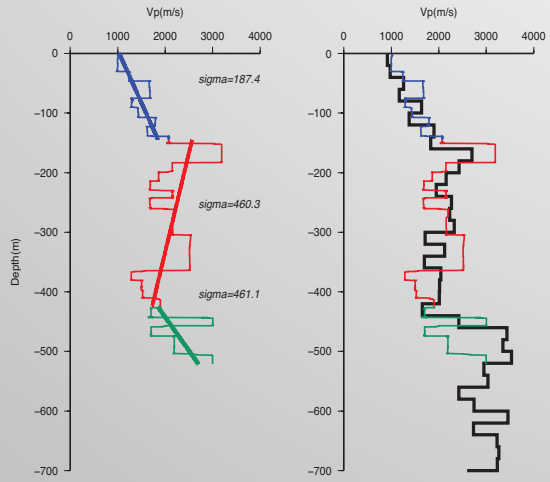
Coda Interferometry (Matzel et al. 2013 Mellor's talk)



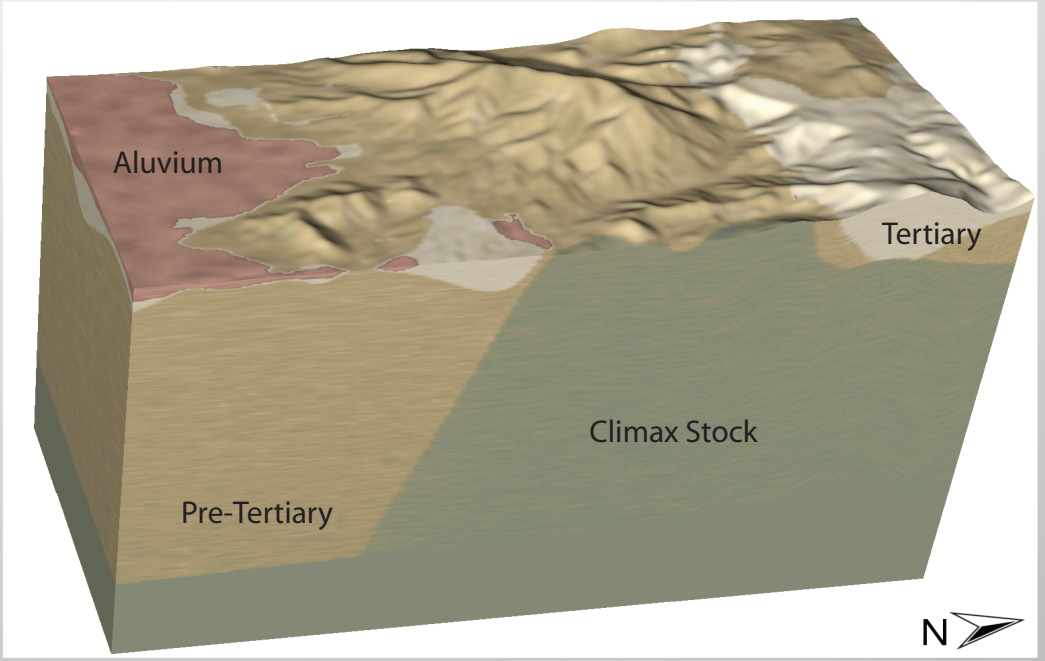


Models of Surface Weathered Layer for L1 (Max Freq 10 Hz)

Small Scale Shallow Variations

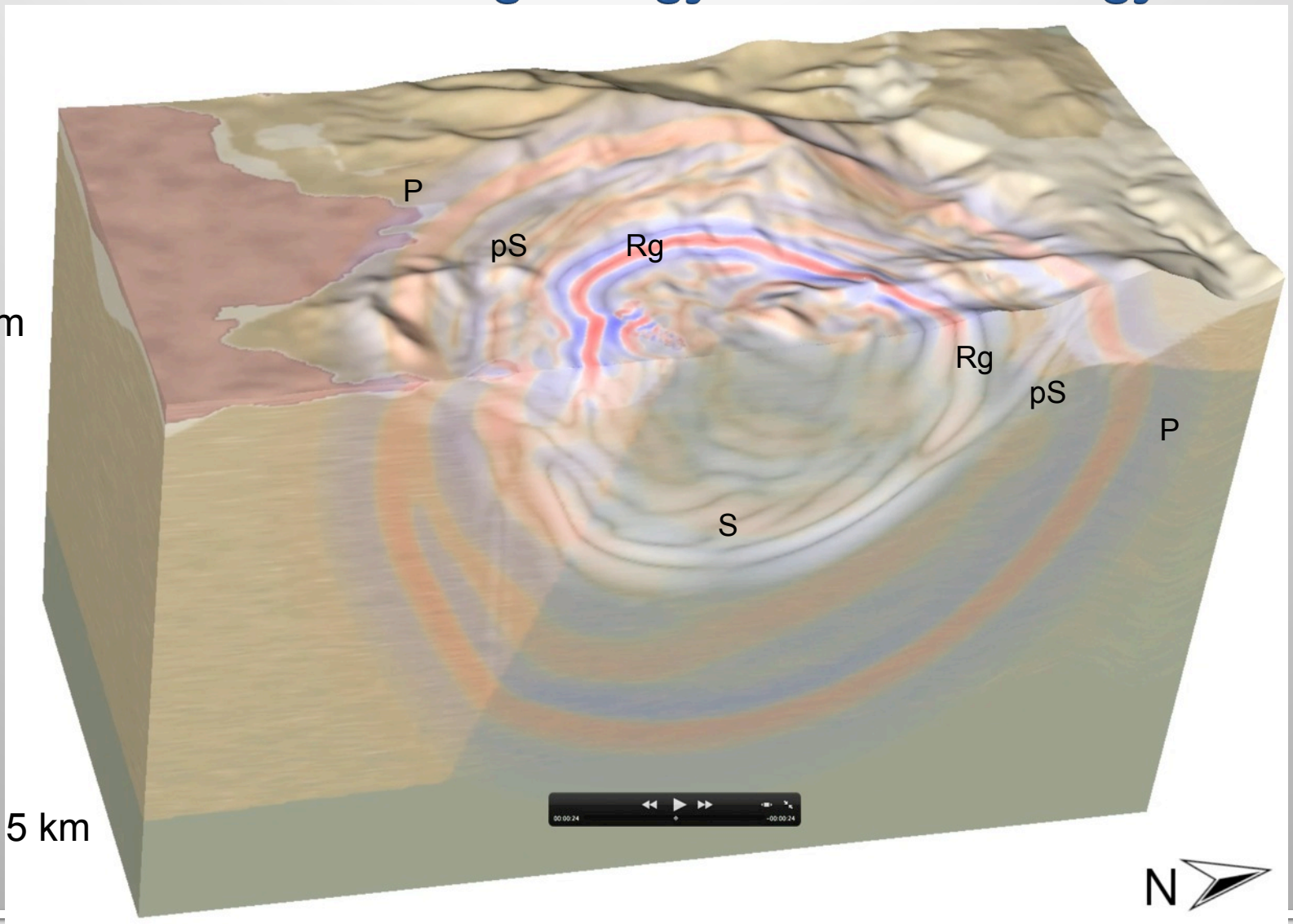


Velocity Model

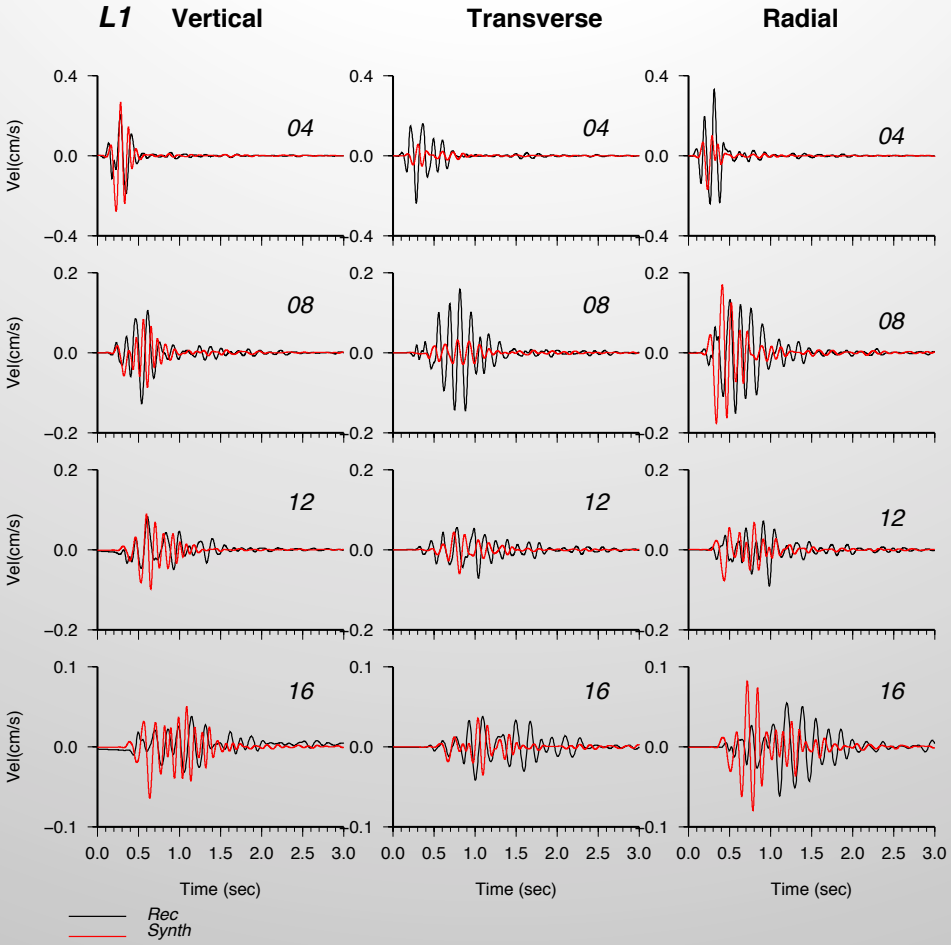


Stochastic Small Scale Heterogeneity
(L=1km,up 15%, Gaussian weighting)

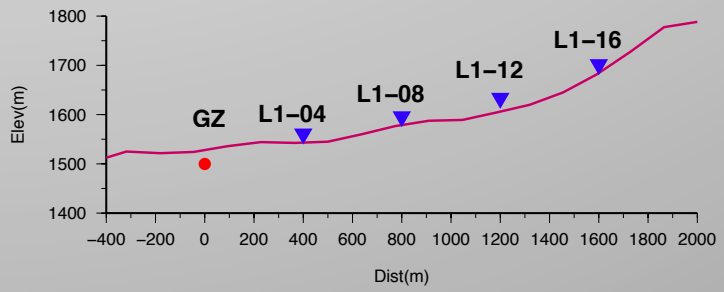
Simulations reveal very complex propagation and clear conversions of P and Rg energy to S-wave energy



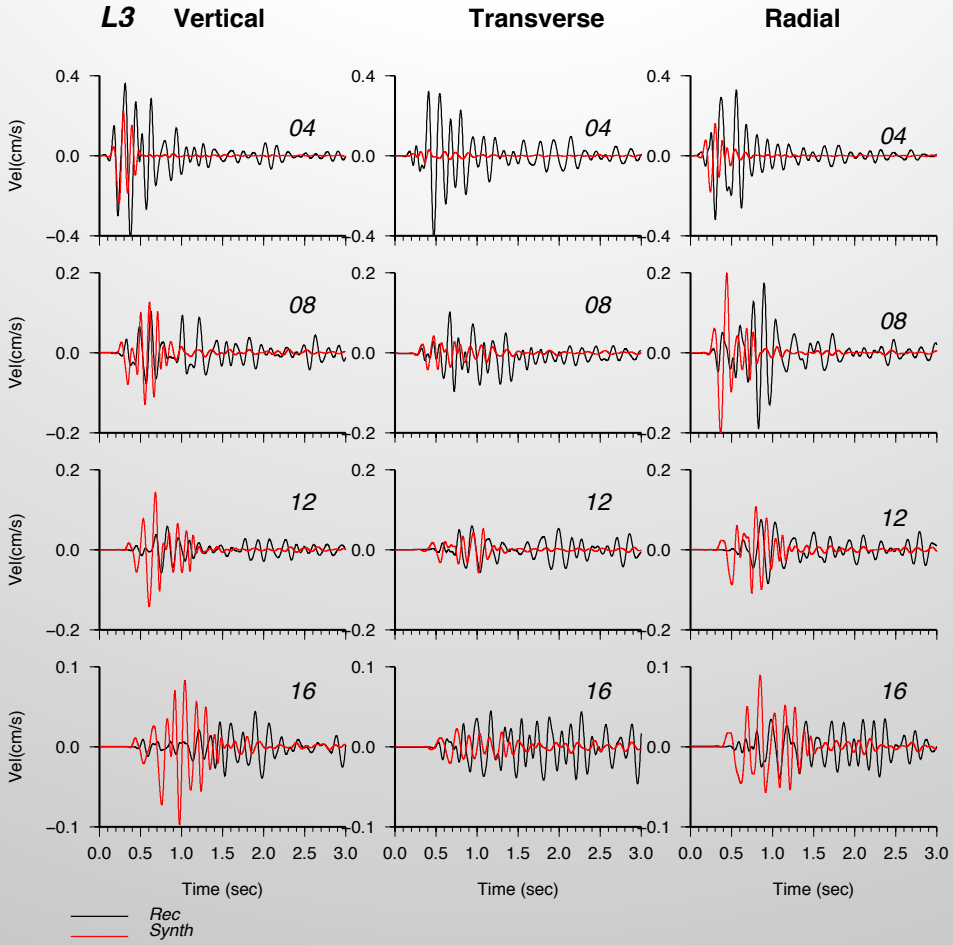
Line 1 Granite



3D Simulation Using Source Coupling
3D Model & Topography
(Max Freq:10Hz)

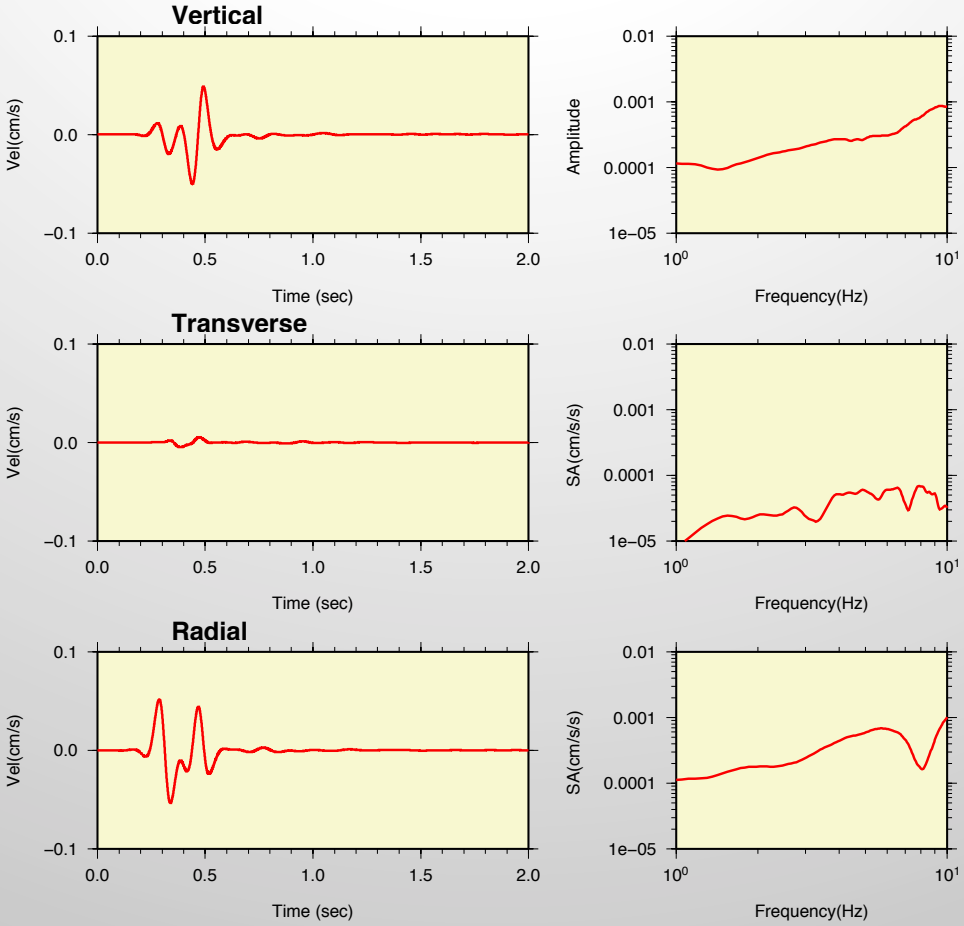


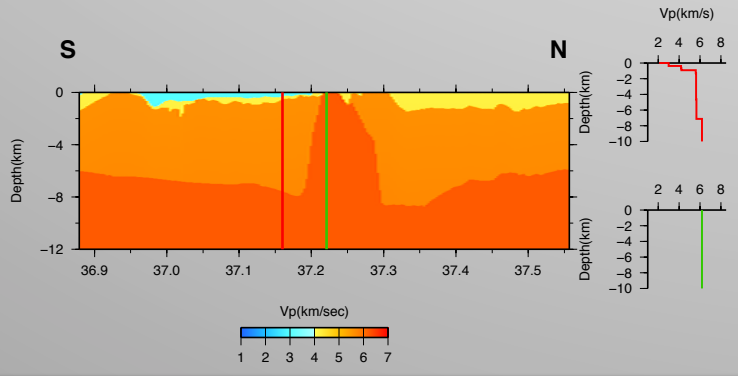
Line 3 Alluvium



The alluvium structure needs improvements

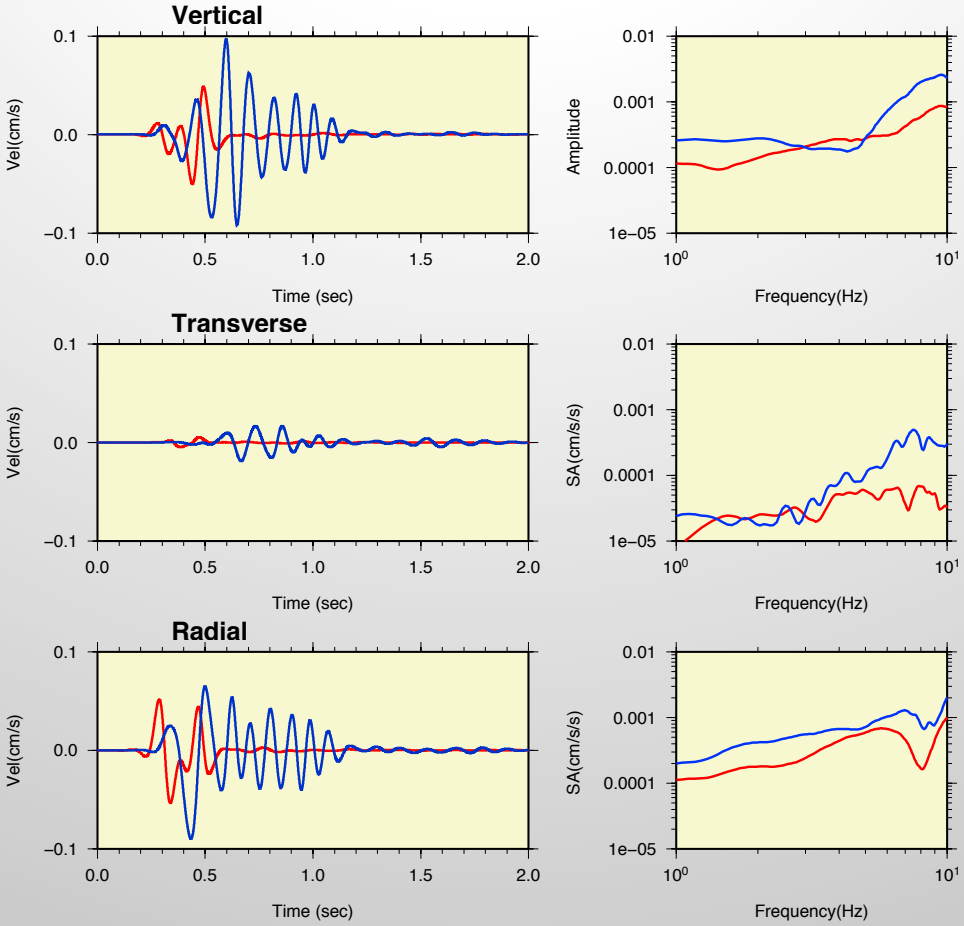
L1-16 Granite

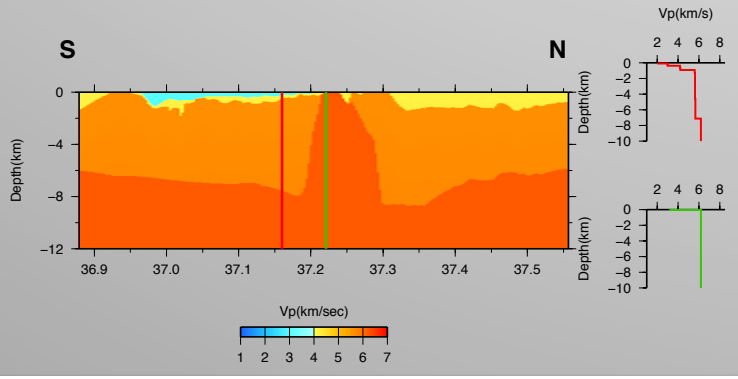




Basic 3D Velocity Model

L1-16

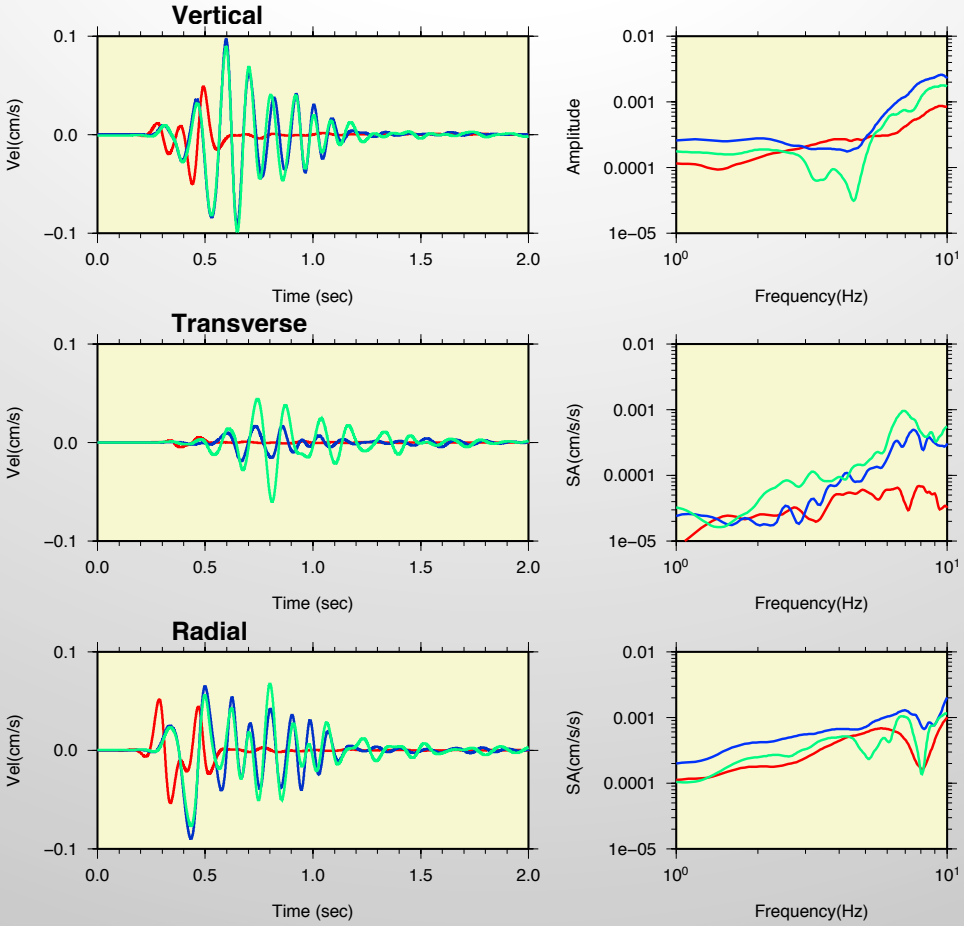


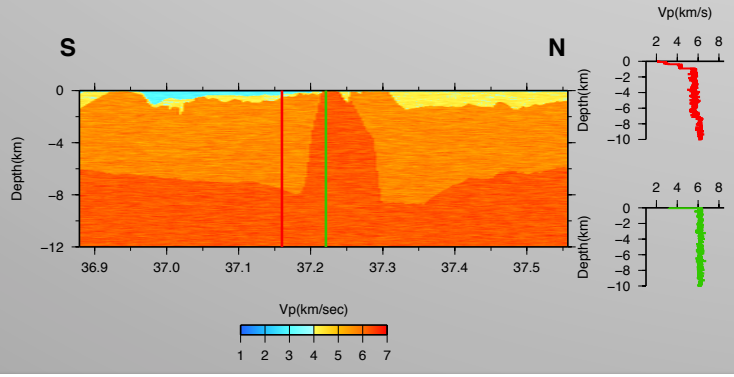


Basic 3D Velocity Model
+ Surface Weathered Layer

Weathered layer increases amplitude and duration

L1-16

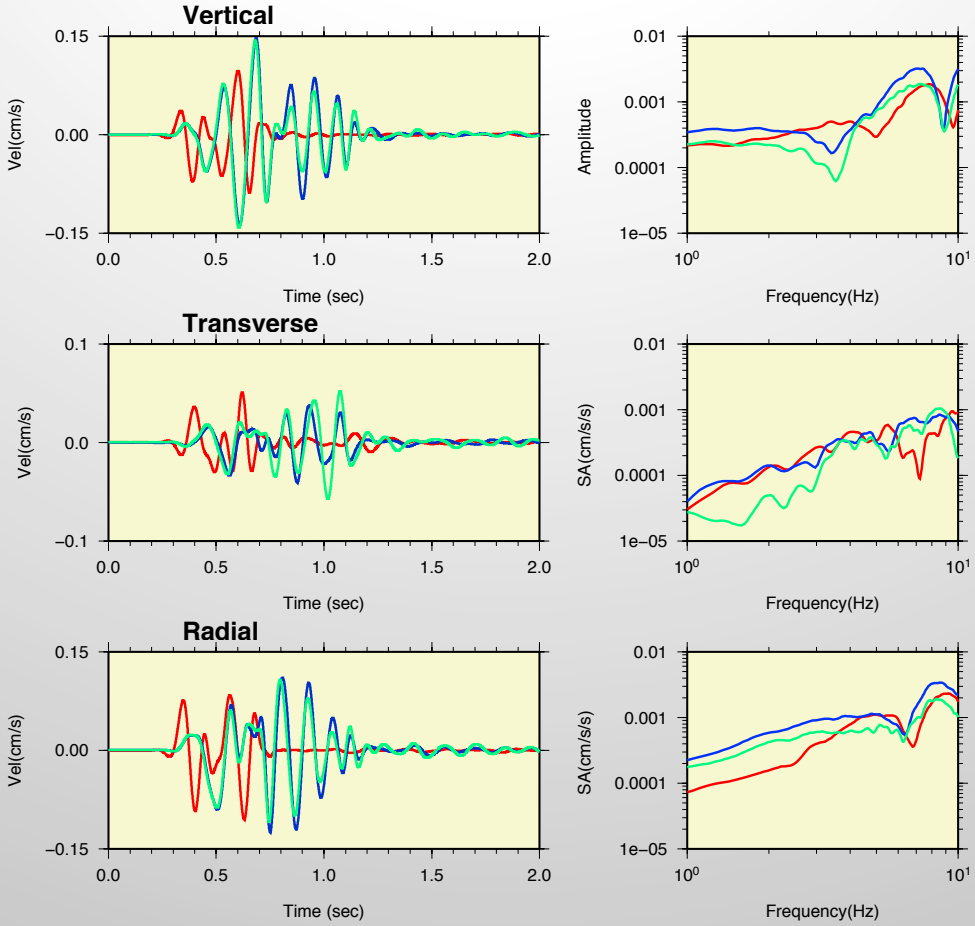


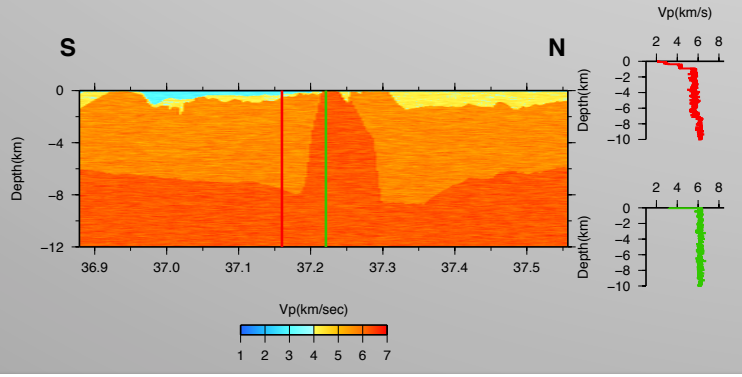


Basic 3D Velocity Model
+ Surface Weathered Layer
+ Topography and Stochastic Heterogeneity (L=1km,up 15%)

Topography and Stochastic Heterogeneity increases amplitude on the transverse component

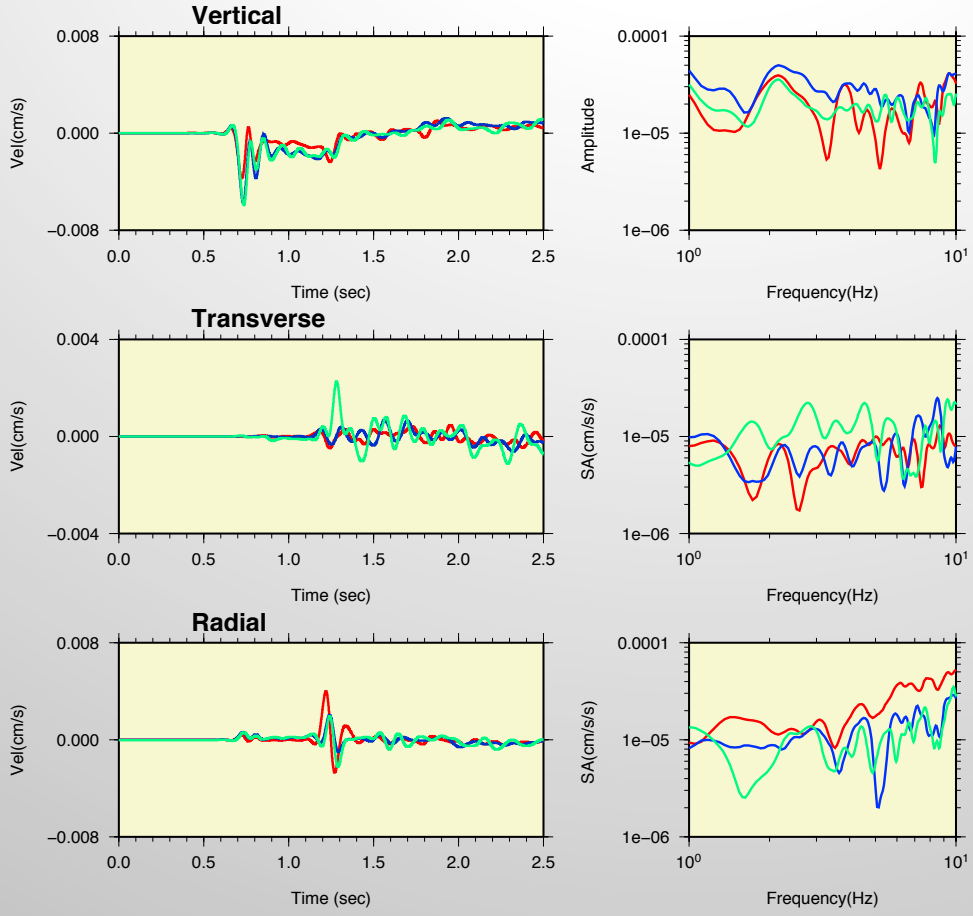
L3-12 Alluvium



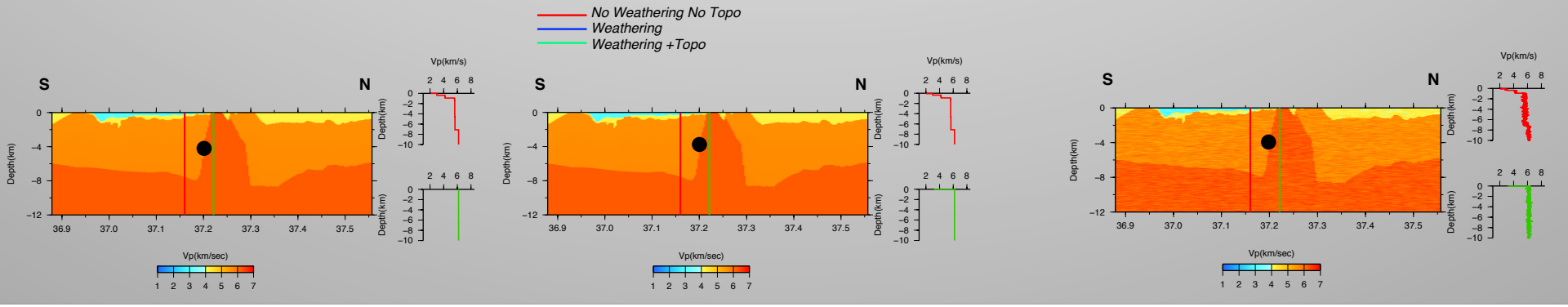


Basic 3D Velocity Model
+ Surface Weathered Layer
+ Topography and Random Variations

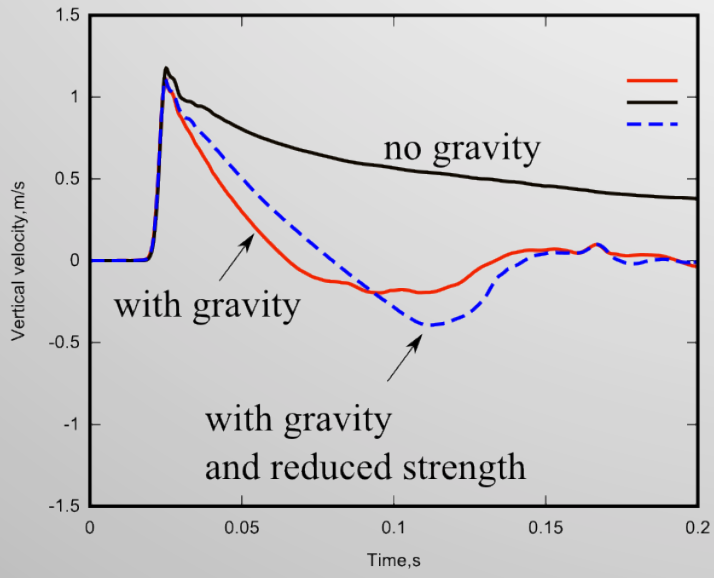
Receiver Located 4 km Below the Source

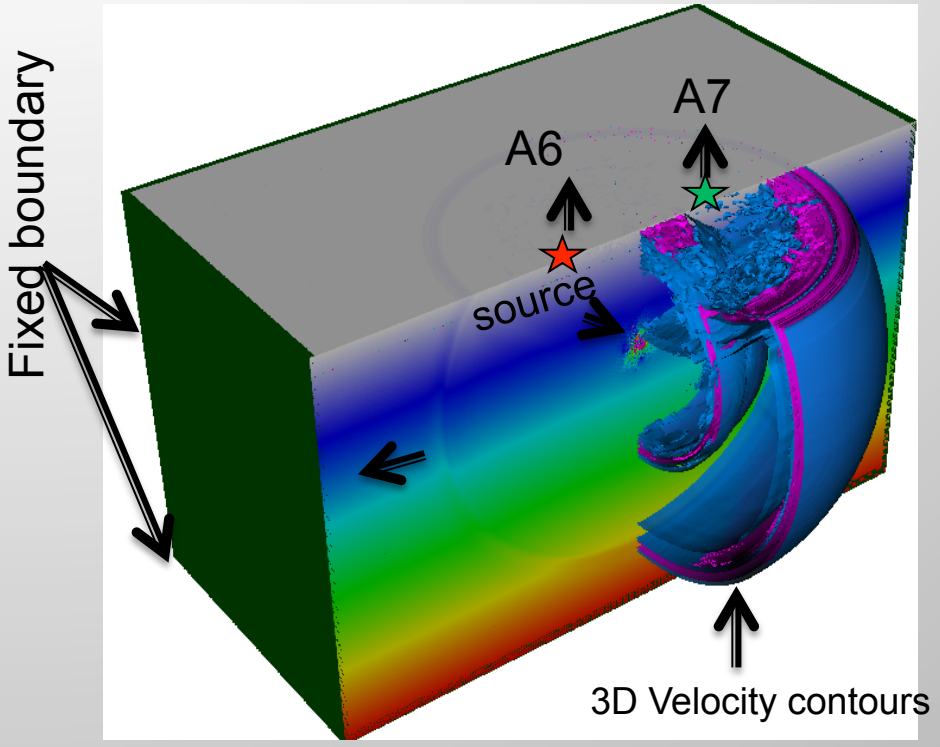


Significant presence of scattering effects local and regional ray paths

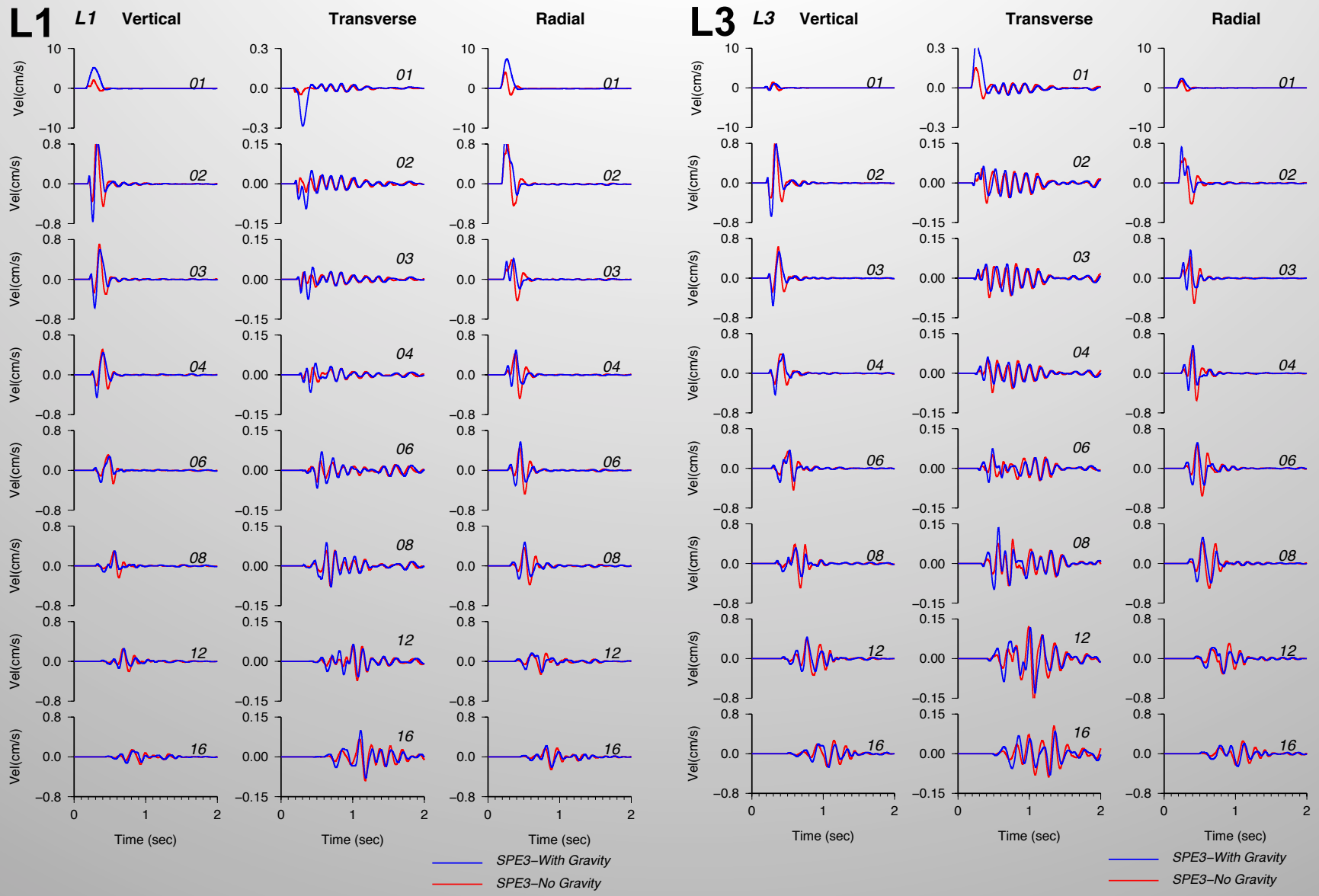


Sensitivity of Far-Field Motion To Source Modeling (Effect of Gravity)





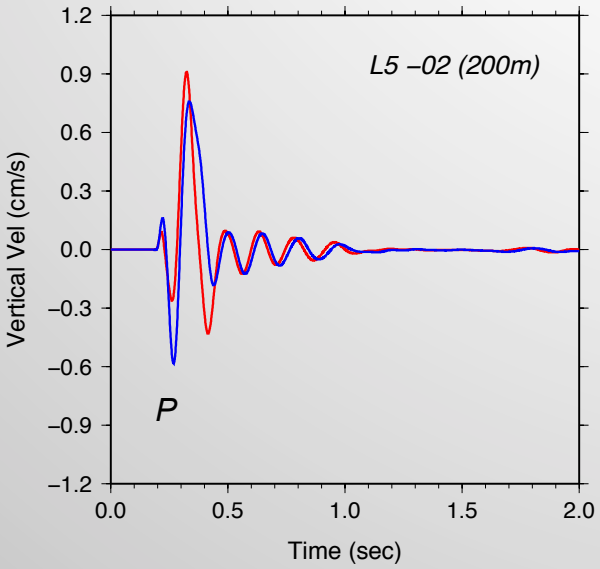
Effects of Gravity

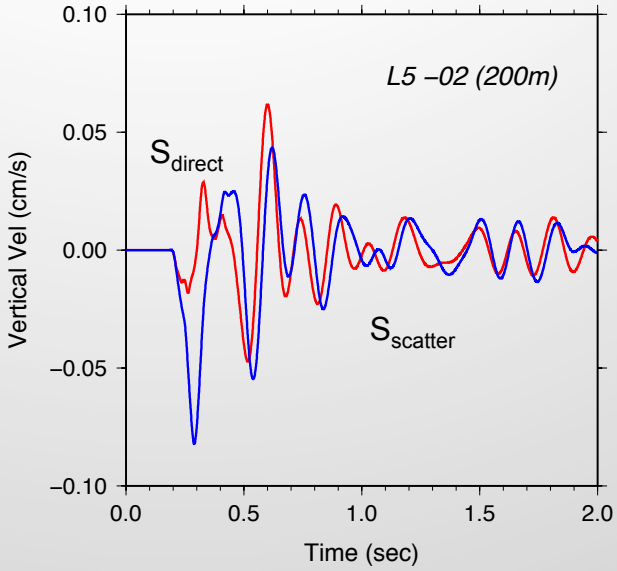


Effects of Gravity Max Freq: 6Hz

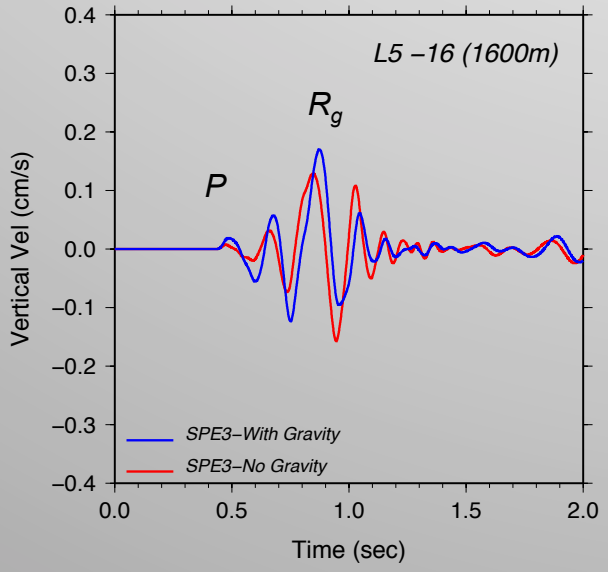
Vertical

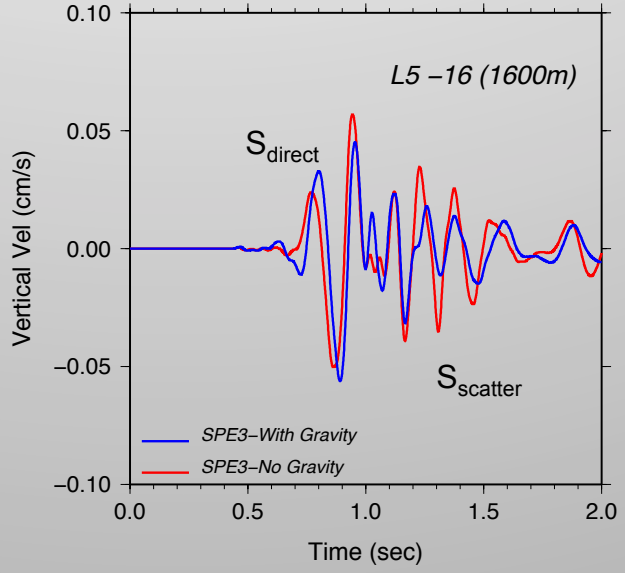
Transverse





200m

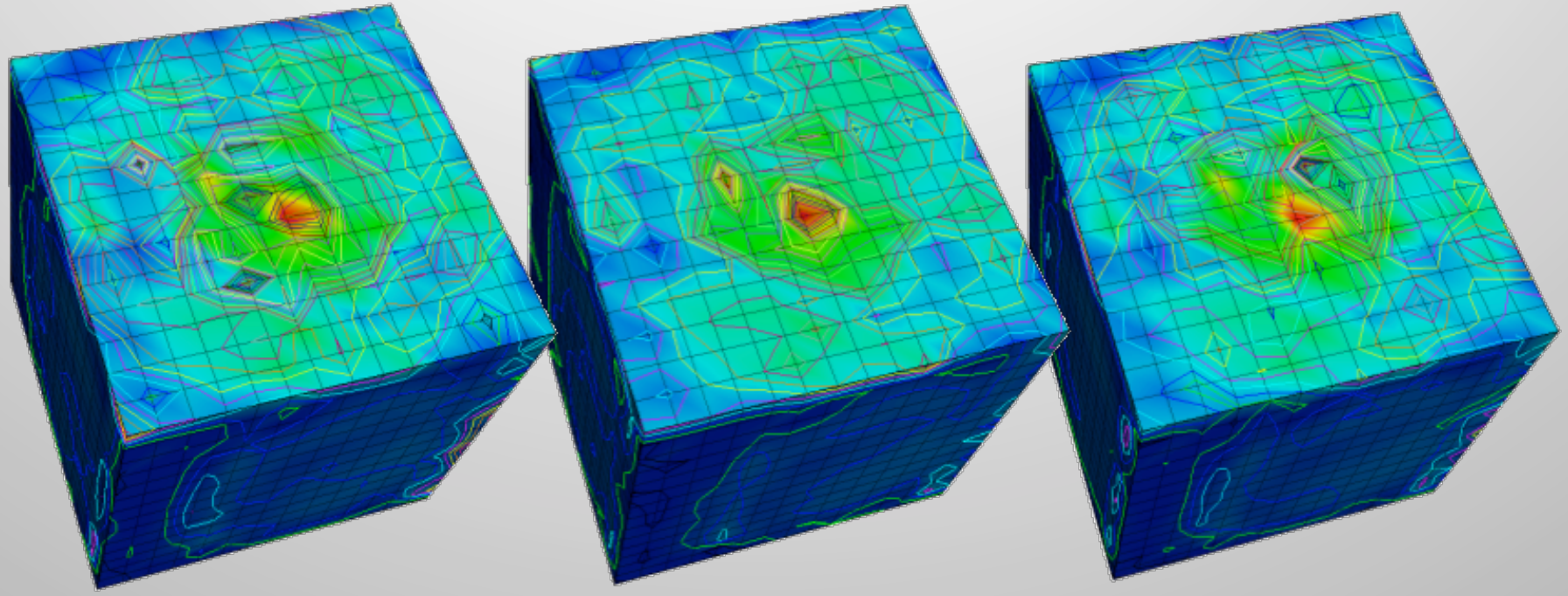




1600m

Sources With Different Equally Probable Joint Network Using Site Fracture Characterization

Model 1 Model 2 Model 3

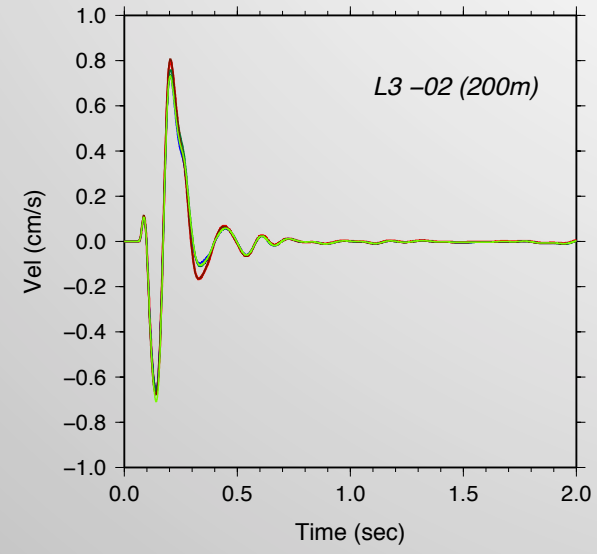


Snapshots of particle velocity amplitude at 10ms, for different sources, computed with 3 different realizations of fracture networks embedded in Geodyn-L.

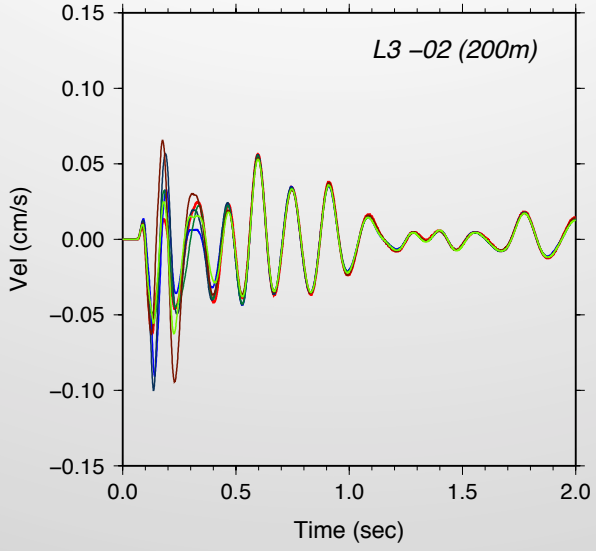
Effects of Joints Orientation on the Far-Field

Max Freq: 6Hz

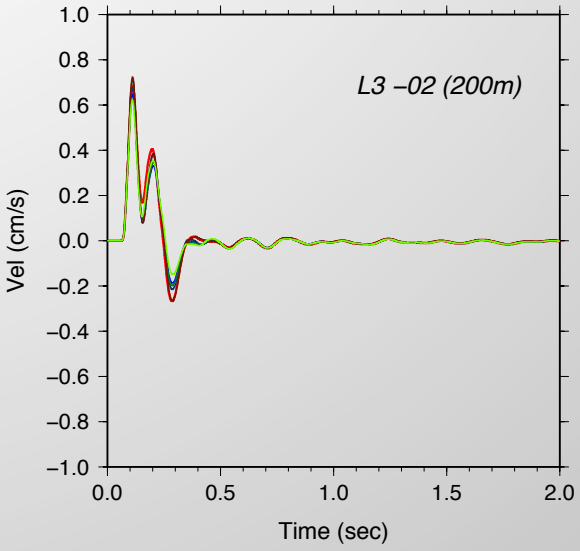
Vertical

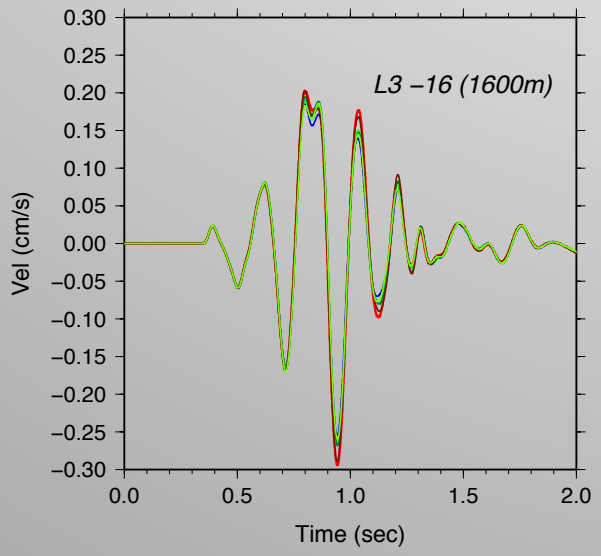


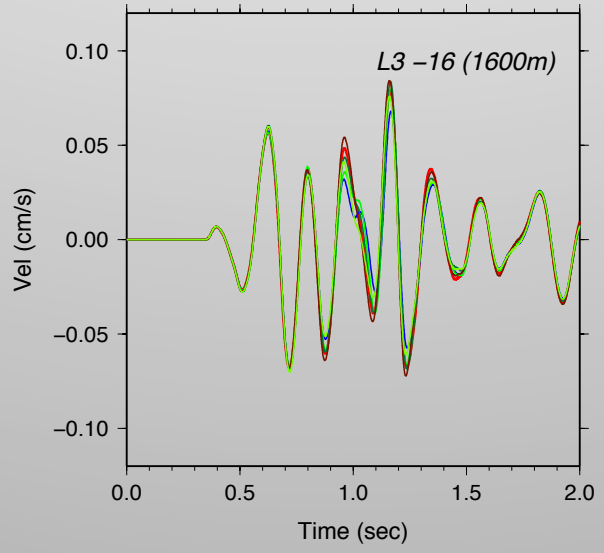
Transverse

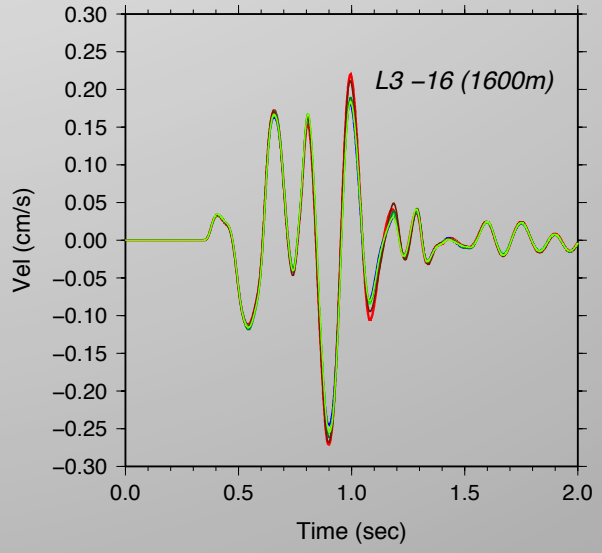


Radial









Conclusions

•Coupling of explosion 3D hydrodynamic simulation with anelastic wave propagation modeling improves the quality of simulated waveforms for the SPE

•The combined effects of surface weathered layer, surface topography and small scale structural heterogeneities have a significant impact on creation and amplitude of shear motion during underground explosions

• In addition to shear waves generated at the source, shear waves generated by near-surface structural complexities propagate at local distances. The increase in shear-wave energy could explain why the P/S discriminant for SPE explosions does not work well for some azimuths at local distances.

• Stochastic realizations of joints based on site fracture characterization produce similar shear and compressive far-field ground motion in the modeled frequency range up to 6Hz.

Thank you!

Acknowledgements